Spatial patterns of variability in Antarctic surface temperature: Connections to the Southern Hemisphere Annular Mode and the Southern Oscillation

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Abstract. The 17-year (1982-1998) trend in surface temperature shows a general cooling over the Antarctic continent, warming of the sea ice zone, with moderate changes over the oceans. Warming of the peripheral seas is associated with negative trends in the regional sea ice extent. Effects of the Southern Hemisphere Annular Mode (SAM) and the extrapolar Southern Oscillation (SO) on surface temperature are quantified through regression analysis. Positive polarities of the SAM are associated with cold anomalies over most of Antarctica, with the most notable exception of the Antarctic Peninsula. Positive temperature anomalies and ice edge retreat in the Pacific sector are associated with El-Niño episodes. Over the past two decades, the drift towards high polarity in the SAM and negative polarity in the SO indices couple to produce a spatial pattern with warmer temperatures in the Antarctic Peninsula and peripheral seas, and cooler temperatures over much of East Antarctica.

1. Introduction

While global temperatures rose by 0.3°C between 1978-1997 [*Jones et al.*, 1999], the spatial distribution of this trend is certainly not uniform. During the last 20 years, pronounced warming of the Antarctic Peninsula [*King and Harangozo*, 1998] has been contrasted by reported cooling at a number of weather stations on the coast and plateau of East and West Antarctica [*Comiso*, 2000]. Recently, the analysis of *Doran et al.* [2002] suggests a net cooling of the Antarctic continent between 1966 and 2000. Over approximately the same period, the warming trend of 0.09°C/yr (1980-1999) at Faraday Station at the northern tip of the Antarctic Peninsula can be compared to the cooling trends of 0.07°C/yr (1986-2000) at the McMurdo Dry Valleys and 0.05°C/yr at the South Pole (1980-1999).

Surface temperature anomalies of the Antarctic are related to anomalies in atmospheric and ocean circulation, and the sea ice cover. A new 17-year (1982-1998) surface temperature (ST) dataset [*Comiso*, 2001] allows us to identify the characteristic spatial patterns of variability in the Antarctic ST field and their relation to large-scale circulation patterns. In this paper, we explore the linear effects of the Southern Hemisphere Annular Mode (SAM) and the Southern Oscillation (SO) on the ST fields of the Antarctic. The SAM describes a predominantly zonally symmetric pattern and is characterized by sea-saws of atmospheric mass between the polar caps regions poleward of 60°S and the surrounding zonal ring centered along ~45°S, as manifested in the leading empirical orthogonal functions (EOFs) of the 850-hPa geopotential height field [*Thompson and Wallace*, 1998]. This annular mode is also related to strong perturbations in temperature and total ozone column over the polar caps during the stratosphere's active season. The SO refers to the seesaw in the surface pressure anomalies between the Indian Ocean-Australian region and the southeastern tropical Pacific on a seasonal and interannual time scale. Linkages between the SO, and the climate and sea ice anomalies of the Southern Ocean have been described by *Kwok and Comiso* [2002]. The SO plays a role in the regional pattern of Antarctic climate changes over the past 20-years. Here, the SO is discussed in the context of potential interactions between the two modes of atmospheric variability.

2. Data Sets and Circulation Indices

The monthly ST fields used in this study are derived from AVHRR (A Very High Resolution Radiometer) infrared data. The dataset, on a 6.25 km grid, covers ocean and ice south of 50°S. Surface temperatures at skin depth provide close estimates of near surface air temperatures. With stable atmospheric stratification over sea ice or ice sheets, these temperatures maybe cooler by several degrees compared to near surface air temperatures. As infrared observations of the surface are available only during cloud-free conditions, the temperatures may not properly reflect the monthly mean. When compared to monthly station data, the cloud-free averages are cooler than the true monthly mean by ~0.5 K. Details of the retrieval procedure and evaluation of the dataset can be found in *Comiso* [2000]. Uncertainties in the retrievals are estimated to be generally less than 3 K over ice-covered surfaces and less than 1 K over open ocean. The data are mapped onto the polar stereographic projection used in SSM/I (Special Sensor Microwave/Imager) data. Monthly anomaly ST fields are produced by removing the monthly climatology at each sample location.

Indices of the SAM are those derived by *Thompson and Wallace* [1998]. These are coefficients of the leading mode in the EOF expansion of the 850-hPa geopotential height field, from 20-90S, from the NCEP/NCAR Reanalysis [*Kalnay*, 1996]. EOF is computed for data from all months, 1958-1997. This mode explains ~27% of the variance of the monthly mean fields poleward of 20°S. The monthly SO indices used in this study are those of the Climate Analysis Center. The SO index is the difference between the standardized Tahiti sea-level pressure (SLP) and the standardized Darwin SLP measurements. Large negative excursions of the SO index are associated with intense El Niño-Southern Oscillation (ENSO) episodes. The time series of the two indices and the mean SLP and wind anomaly patterns associated with the positive polarity of these atmospheric indices are shown in Fig. 1.The most striking features associated with the positive polarity of the SAM index are the lowered SLP within the circumpolar trough, enhancement of the westerlies north of 70°S, and negative anomalies in the meridional wind west of the Antarctic Peninsula. For the positive polarity of the SO, lowered SLP is found centered over the Amundsen and Bellingshausens Seas, with corresponding meridional and zonal wind anomalies. Negative polarities of the SAM and SO indices exhibit the same spatial patterns of anomalies but of opposite polarities.

3. Results and Discussion

The 17-year (1982-1998) trends of the ST and ice edge anomalies are shown in Fig. 2. The most pronounced feature on the map is the warming of the sea ice zone around Antarctica. It should be emphasized that the trend over sea ice should be interpreted with care, as the retrievals over sea ice are highly variable because the STs are dependent on ice thickness and ice concentration. The ST of thin ice is closer to the freezing point at the bottom boundary (sea water at ~-1.8°C) while the ST of thick ice is closer to that of the air temperature. With sea ice in the 0-1 meter range, as is typical in the Southern Ocean, there could be significant contrasts between ice and air temperatures. Ice concentration anomalies are results of openings and closings of the ice cover due to gradients in ice motion. During the fall and winter, it is estimated that the ice concentration within the ice pack is generally close to 100% with ~10% of this being newly frozen leads [*Comiso and Steffen*, 2001]. Thus this overall trend may also be potentially interpreted as expressions of lower ice concentration and/or a thinner ice cover. Little seasonality is observed in this warming pattern. Regions with negative trend in the ice edge are coincident with areas with warming. The two sectors, west of the Ross Sea and east of the Antarctic Peninsula in the Weddell Sea, showing cooling trends are coincident with positive trends in the ice edge.

Away from the sea ice zones, the temperature trends are more moderate with a weak warming of West Antarctica. Except for the strip of warming at the highest elevations (above 3.5 km) of the East Antarctic plateau, a general cooling of the interior is evident. Examining the annual anomaly maps (not shown here), this strip of warming can be attributed to warm anomalies occurring between 1995 and 1997 but absent during other years. The largest cooling can be found around the South Pole and the region around Dome C. As discussed in *Comiso* [2000], the regional trends are consistent with the polarity of the trends obtained at weather stations.

The changes in the local ice surface temperatures and SSTs based on linear regression with the SAM and SOI indices are presented in Fig. 3. The regression maps show the changes in temperature corresponding to a unit deviation in the SAM or SO indices. A dipole pattern can be seen in the SAM regression map. Warming of more than 1°C associated with one positive unit of deviation change in the SAM index occur over a region to the east and west of the Antarctic Peninsula. The upward trend in the SAM index accounts partially (0.04°C/yr) for the observed warming over the Antarctic Peninsula during the past 17-years. The enhanced surface westerlies (Fig. 1) suggest that the warming could be attributed to an increase in the advection of relatively warm oceanic air over the cold land, indeed with preferential warming of the west coast of the Peninsula [*Vaughan and Doake*, 1996; *Thompson and Wallace*, 2000a]. This warming is also associated with the recent negative trend in the sea ice extent in the Bellingshausen Sea (Fig. 2) [*Kwok and Comiso*, 2002; *King and Harangozo*, 1998; *Jacobs and Comiso*, 1997; *Jacobs and Comiso*, 1993]. The total observed warming is probably magnified by this regional temperature/sea ice feedback. However, when the ice edge anomalies are regressed upon the SAM index, the coefficients are negligibly small (Fig. 4) indicating little relation between the ice edge and the SAM. This will be discussed further below.

In contrast, negative regression coefficients are obtained over the rest of Antarctic continent, with negative ST anomalies associated with the SAM over the East Antarctic plateau. Positive polarity of the SAM index is associated with cold anomalies over most of Antarctica with the center of action over the East Antarctic plateau. Thus, positive (negative) polarity of SAM is associated with warmer (cooler) temperatures at the Antarctic Peninsula region while the opposite behavior is expected over the continent, indicating an oscillation in surface temperature linked to the SAM. Near the centers of action, the SAM accounts for more than 35% of the variance of the temperature anomalies (Fig. 3).

The relationship between the Southern Oscillation and the Southern Ocean climate and sea ice anomalies have been examined by *Kwok and Comiso* [2002], although the continent effects were not included in their analyses. Compared to the SAM results, regression shows a generally weaker association between the SO and the surface temperature over the Antarctic continent. The pattern of temperature change associated with the SO indices shows a warming of the Antarctic Peninsula associated with a positive excursion of the SO index. The regions of extremes in correlation with the SO indices remain in the sea surface temperature (SST) fields off the Ross Sea (negative correlation) and a sector off the George V and Oakes coasts (positive correlation). Warmer (cooler) SSTs off the Ross Sea are associated with the negative (positive) polarity of SO index, with the opposite behavior found in the other regions. It is interesting to note that a weak negative ST anomaly near the Antarctic Peninsula region is actually associated with ENSO episodes. Regression of the ice edge anomalies upon the SO index show significant variations associated with the SO (Fig. 4) especially in the Amundsen and Bellingshausen Seas.

The relationship between the SAM and SO indices is weak. Over the 17-years, the two are correlated at -0.1. Spatially, the SAM accounts for more of the ST variability within the ice cover (which includes sea ice and ice sheet) while the SO accounts for more of the changes in the ice edge and SST variability in the Pacific Sector of the Southern Ocean. In the 17-year record, the SAM index have trended towards more positive values (1958-2000 trend: 0.3/decade) while the SO index have drifted toward more negative values since the beginning of the period (1958-2000 trend: -0.17/decade). Broadly, this indicates a drift toward a spatial pattern with warmer temperatures around the Antarctic Peninsula, and cooler temperatures over a much of the continent with enhanced westerlies (Fig. 1) associated with the SH annular mode. This pattern occurs along with warmer SSTs in the Pacific Sector of the Southern Ocean and retreat of the ice edge associated with the negative polarities of the SO index (the opposite polarity of the pattern shown in Fig. 1). It is interesting to note that occurrences of opposite polarity in the SAM and SO indices suggest an atmospheric circulation pattern with enhanced westerlies and ice edge retreat that could amplify the temperature/sea ice feedback conducive to the regional warming of the Antarctic Peninsula. The prevalence of this coupled mode of variability over the last 17-years can be seen in the difference between the two indices (Fig. 5). The positive trend (1958-2000 trend: 0.47/decade) and significant bias toward positive polarity in this difference are remarkable. Thus, it seems that the regional warming of the Antarctic Peninsula could be associated with the possible interactions of the modes of atmospheric variability described by the two indices. However, it should be noted that linear regression techniques do not account for feedback (nonlinear) effects and the potential complex coupling between the two atmospheric modes.

4. Conclusions

Observed changes in the surface temperature of the Antarctic appear to be are linked to variations in the extratropical SH annular mode and the extrapolar Southern Oscillation. Spatially, it is clear from Fig. 2 that the SAM and SO indices do not explain the same ST variances, as the two indices are almost uncorrelated. The SAM plays an important role in the circulation pattern and the spatial temperature distribution of the Antarctic sea ice and ice sheet. In surface temperature, positive (negative) polarities of the SAM indices are associated with the positive (negative) temperature anomalies over the Antarctic Peninsula and negative (positive) temperature anomalies over much of the continent. The regions of extremes in correlation with the SO indices are found in the SST fields off the Ross Sea (negative correlation) and sector off the George V and Oakes coasts (positive correlation). Warmer (cooler) SSTs off the Ross Sea is associated with the negative (positive) polarity of SO index, with the opposite behavior found in the other region. This analysis serves to illustrate the importance of the circulation changes associated with the SAM and SO in determining the spatial pattern of surface temperature anomalies. The claim of this study is not that the SAM and the SO indices provide the best fit to the Antarctic temperature anomalies, rather the indices were selected because they relate to well-understood circulation anomalies over that have persisted for much of the past two decades.

The upward trend in the SAM index accounts partially for the observed warming over the Antarctic Peninsula during the past 17-years while the downward trend in the SO index accounts for the retreat of the ice edge in the Bellingshausen Sea west of the Antarctic Peninsula. The significant and prolonged positive trend and bias in the difference between the SAM and SO indices (positive SAM and negative SO) during the past 17-years gave rise to this regional pattern with positive ST anomaly and reduced sea ice cover. We suggest that the total observed warming of the Antarctic Peninsula can be associated with the potential coupling of the modes of atmospheric variability described by the two indices through regional positive temperature/sea ice feedback. Regardless of the cause, the changes in the circulation since the early 80s have resulted in a particular ST anomaly pattern that has amplified warming of the Antarctic Peninsula because of the interactions between ice and ocean.

The source of variability of the SAM has not been established. It is interesting to note that the variability of the tropospheric SH annular mode has been shown to be related to changes in the lower stratosphere [*Thompson and Wallace*, 2000b]. The high index polarity of the SH annular mode is associated with the trend toward a cooling and strengthening of the SH stratospheric polar vortex during the stratosphere's relatively short active season in November, and ozone depletion. A causal mechanism was suggested by recent Antarctic data showing a strong cooling trend in the lower stratosphere that are consistent with recent ozone depletions [*Randel and Wu*, 1999]. However, it the primary mechanism that is responsible for the recent trend in the SH annular mode remains to be determined.

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Figure 1. The indices of the Southern Hemisphere annular mode (SAM) and the Southern Oscillation from 1978-2000, and the composites of SLP, and zonal and meridional wind anomalies associated with their positive polarities (SAM index > 0.5; SO index > 0) of the indices. The SLP and wind anomalies are derived from NCEP/NCAR analyses. The trends (1958-2000) in the indices are also shown.

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Figure 3. The regression **R** and correlation maps **C** over the 17-year period obtained by regression of the surface temperature anomalies upon the SAM and SO indices. The regression coefficient indicates changes in temperatures corresponding to a unit change in the indices. The temperature variations explained by the SAM and SO indices at the extremes of correlation (identified by arrows on the maps) are shown. Contours on the regression map show the 99% confidence levels and contours on the correlation map show the ±0.4 correlation levels.

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Figure 4. Regression of the ice edge anomalies upon the SAM and SO indices (1982-1998). The regression coefficient indicates deviations in ice edge location (unit: degree of latitude) corresponding to a unit change in the indices. The correlation coefficient is also shown. Note the different scales in the regression coefficients of the two plots.

Figure 4. Regression of the ice edge anomalies upon the SAM and SO indices (1982-1998). The regression coefficient indicates deviations in ice edge location (unit: degree of latitude) corresponding to a unit change in the indices. The correlation coefficient is also shown. Note the different scales in the regression coefficients of the two plots.

Figure 5. Difference between the SAM and SO indices from 1978-1998 and the composite field of monthly surface temperature anomalies for SAM-SOI > 1.5. The trend (1958-2000) in the difference is also shown.

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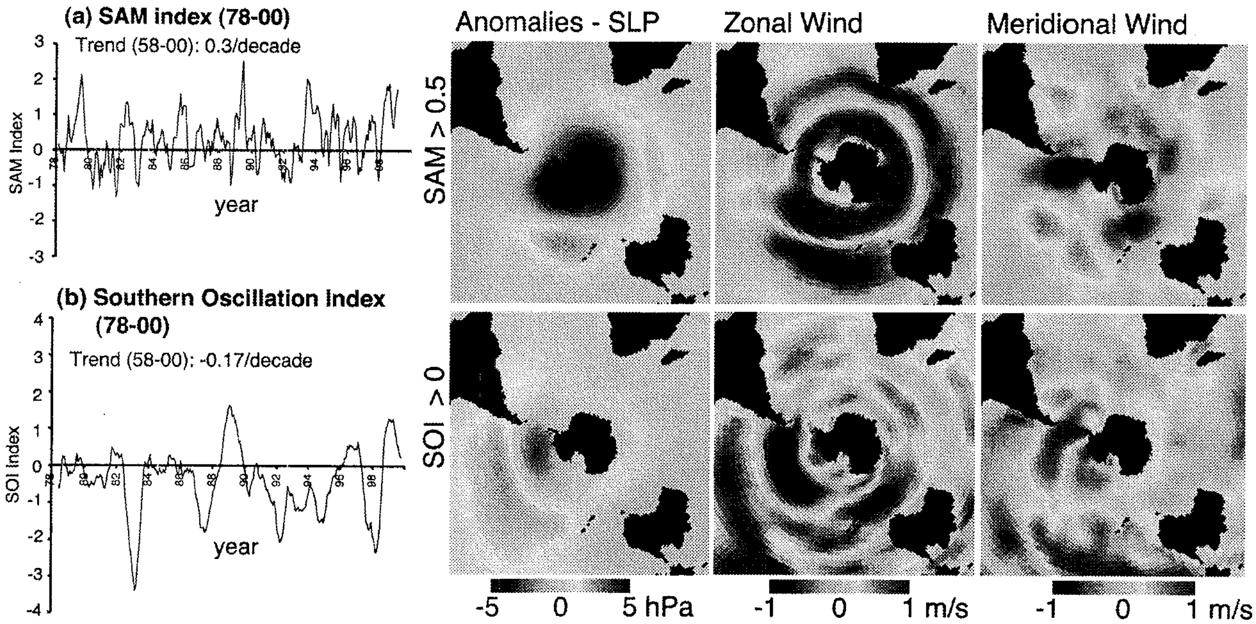
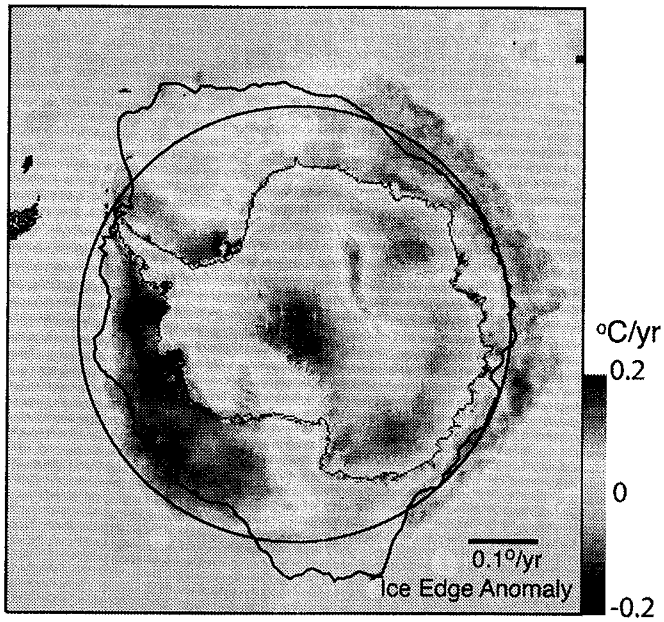


(a) SAM index (78-00)
Trend (58-00): 0.3/decade
SAM Index
year
(b) Southern Oscillation Index (78-00)
Trend (58-00): -0.17/decade
SOI Index
year
Anomalies - SLP
Zonal Wind
Meridional Wind
SAM > 0.5
SOI > 0
-5 0 5 hPa
-1 0 1 m/s
-1 0 1 m/s

Fig. 1

Fig. 2



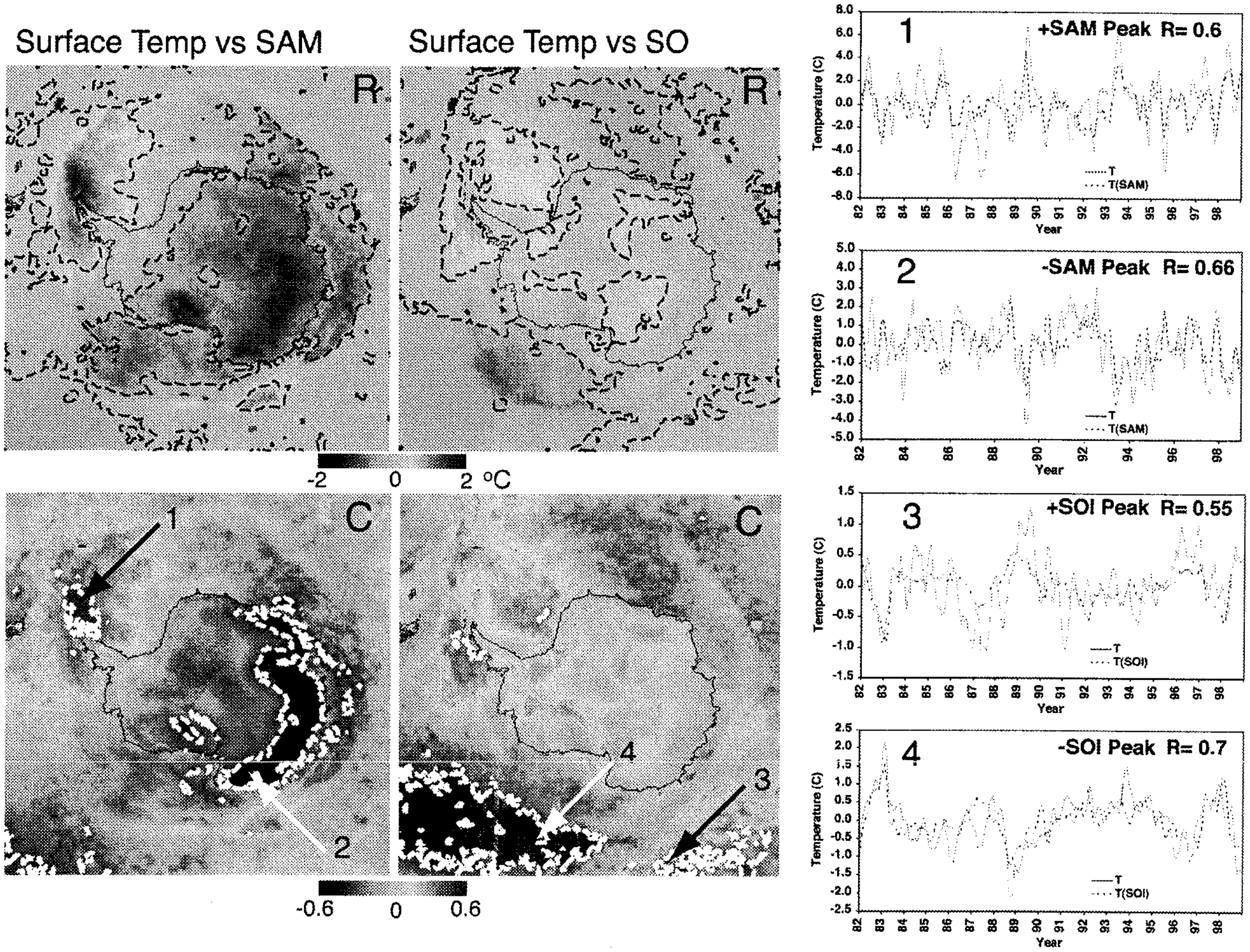

Surface Temp vs SAM
Surface Temp vs SO
R
R
-2
0
2 °C
C
C
1
2
3
4
-0.6
0
0.6
1
+SAM Peak R= 0.6
2
-SAM Peak R= 0.66
3
+SOI Peak R= 0.55
4
-SOI Peak R= 0.7
Temperature (C)
Year
T
T(SAM)
T(SOI)

Fig. 3

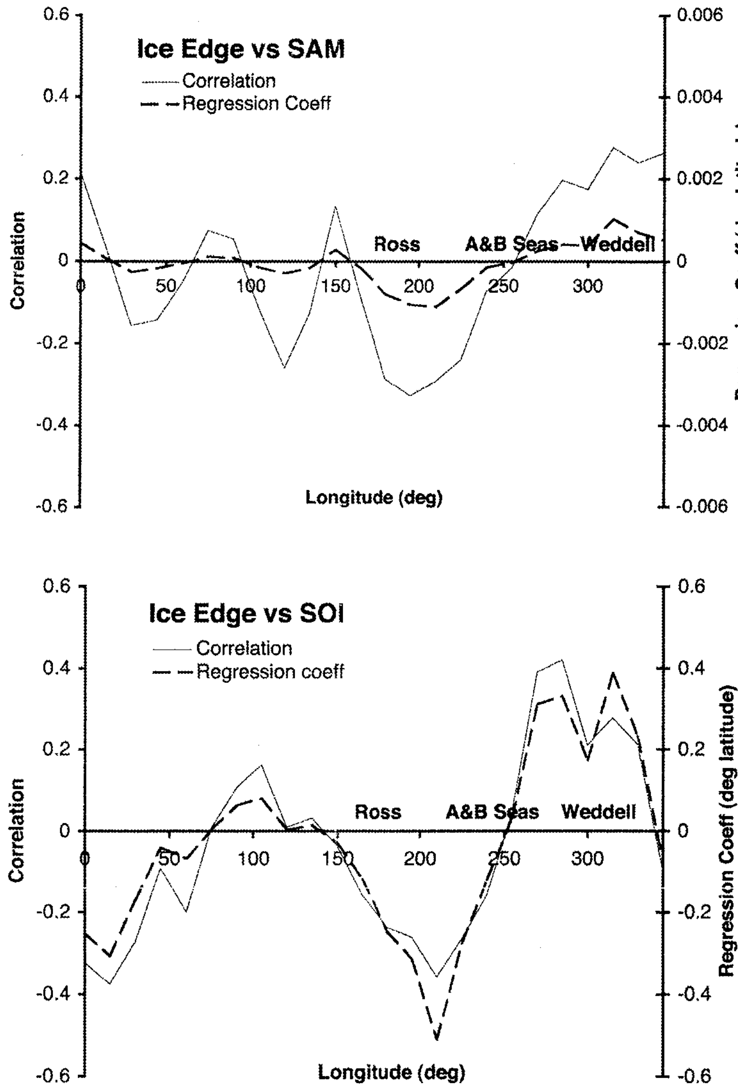

Ice Edge vs SAM
Correlation
Regression Coeff
Ross
A&B Seas
Weddell
Correlation
Regression Coeff (deg latitude)
Longitude (deg)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0.006
0.004
0.002
-0.002
-0.004
-0.006
50
100
150
200
250
300
Ice Edge vs SOI
Correlation
Regression coeff
Ross
A&B Seas
Weddell
Correlation
Regression Coeff (deg latitude)
Longitude (deg)

Fig. 4

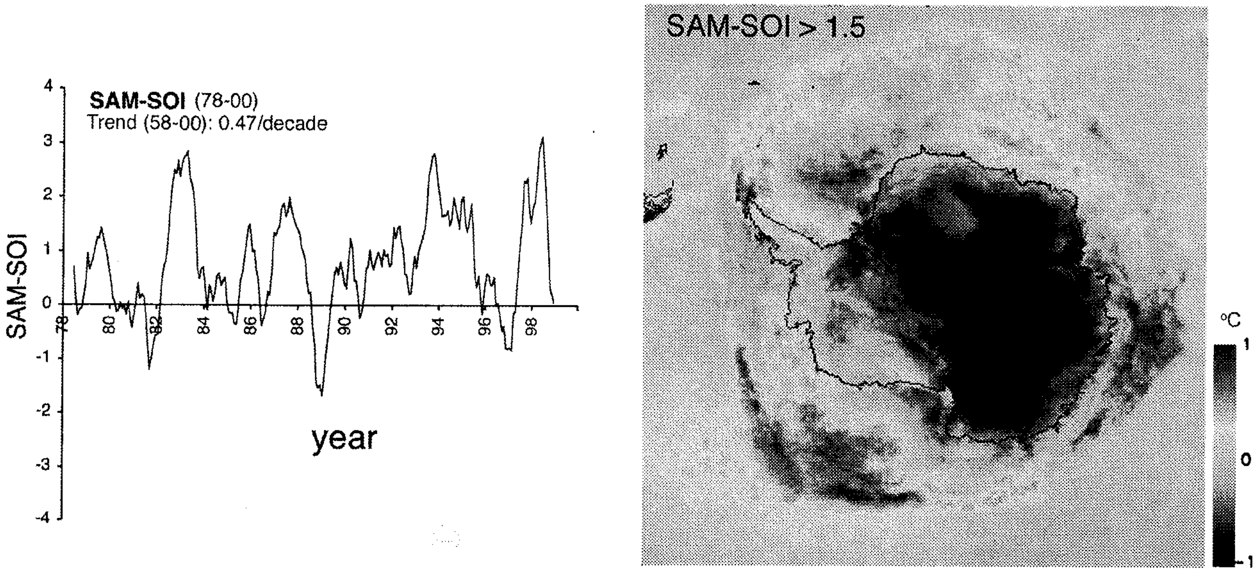

SAM-SOI (78-00)
Trend (58-00): 0.47/decade
SAM-SOI
year
4
3
2
1
0
-1
-2
-3
-4
78
80
82
84
86
88
90
92
94
96
98
SAM-SOI > 1.5
°C
1
0
-1

Fig. 5